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Abnormal Operation of Transformers

Electrical Engineering

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ABNORMAL OPERATION OF TRANSFORMERS

BY

CARL ELMER MERRIS
AND
GLENNVILLE EDWARD STEWART

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

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May 31, 1912

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

CARL ELMER MERRIS AND GLENNVILLE EDWARD STEWART

ENTITLED ABNORMAL OPERATION OF TRANSFORMERS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

Arvid R. Anderson
Instructor in Charge

APPROVED: Ernst Berg

HEAD OF DEPARTMENT OF ELECTRICAL ENGINEERING.

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INTRODUCTION.

In practice the engineer has to meet conditions as they are, not as he would like to have them with everything running smoothly. He has to instruct those under him how to do things that come up in the course of his work, and often has to go to the scene of an accident and undo the work of a careless or ignorant employee. It is the purpose of this paper to present conditions which might arise in every day practice, study the underlying principles and indicate how satisfactory operation may be brought about, where this is possible.

The explanations given are all based upon experiments performed in the laboratory. Since relative, rather than exact figures are of interest, masses of data have not been entered herein. The investigations have been confined to transformers, yet with this apparently narrow restriction the field for investigation is wide and almost impossible to cover completely. Here it has been the object to study the working out of some of the more important principles, leaving untouched many considerations that might be taken up in an exhaustive treatise. It has been the object to obtain practical and theoretical instruction rather than to pursue a course of investigations with the purpose of adding to the realm of science.

II. DETERMINATION OF TRANSFORMER CONSTANTS.

The constants of a transformer have to be known before any predictions can be made or any conclusions drawn as to its behavior when operating in multiple with other transformers. The determination of these is somewhat elementary yet it is deemed advisable to give a sample calculation here.

G.E.Transformer. #745828. 5 K.W., 110/220--1100/2200

Resistance of secondaries in series.----0.095 ohm.

Resistance of primaries in parallel.----2.000 ohm.

To get a 20 to 1 ratio, which was the one desired in this particular case, the secondaries must be in parallel, primaries in series. This will give

Secondary resistance -------- 0.024 ohm.

Primary resistance --------- 8.000 ohm.

Full load secondary current = $\frac{5000}{110}$ = 45.4 amperes.

Full load primary current = $\frac{45.4}{20}$ = 2.27 amperes.

Equivalent resistance of secondary referred to primary resistance = $20^2 \times 0.024 = 9.6$ ohms.

Total equivalent resistance = $(8 + 9.6) = 17.6$ ohms.

$17.6 \times 2.27 = 40$ volts, total IR drop.

$\frac{40}{2200} = 0.0182$ or 1.82% resistance, total.

Impedance Test (secondary short circuited)

Volts drop = 61 volts at full load secondary current.

$\frac{61}{2200} = 0.0277$ or 2.77% total impedance.

Since $x = \sqrt{z^2 - r^2}$, $x = \sqrt{(0.0277)^2 - (0.0182)^2}$

$= 2.08\%$ total x.

x primary = x secondary = 1.04%.

REGULATION.

The regulation of a transformer is defined as the drop in voltage from no load to full load expressed as percent of full load voltage. In parallel operation it is essential that the transformers have nearly the same regulation, otherwise the one with the best, that is smallest per cent, regulation will take more than its share of the load. This is obviously due to the fact that its voltage is not decreased as much when the load comes on as is that of one with poorer regulation. Hence it will take the load until the impedence drop brings its terminal voltage down to a value equal to that of the other transformer. This may reach a point where the machine is seriously overloaded, causing excessive heating and attendant losses. As the sample calculation of regulation will show, the ideal requirements for parallel operation are that the transformers shall be exactly similar. That is, the percentage resistance, reactance, and exciting currents shall be exactly the same. The regulation curves will be exactly alike and the transformers will divide the load in proportion to their capacities. It is impossible to build two transformers which will meet these requirements completely, but if they are of the same type and made by the same company, they will usually be so nearly alike that their

regulations will be almost identical when computed from readings taken on instruments of the usual degree of accuracy. For instance, the regulation of the three 5 K.V.A. G.E. Type H transformers were found to be 1.84%, 1.835%, 1.84% respectively. As a rule it is hard to get transformers made by different companies to operate satisfactory in parallel, owing to different constants and regulations. A load division within ten per cent of apparent correct value is generally as close as may be expected in the paralleling of power transformers of different makes. Lighting transformers must have good regulation in order to keep satisfactory voltage upon the lines at all times. It was found that with the four kinds of lighting transformers tested for such a load division no trouble arose from this source. Calculations showed that the greatest difference in regulation existed between the 3 K.V.A. Westinghouse and the 2 K.V.A. G.E., and yet they divided the load well under the ten per cent limit allowed. This held in a general way for inductive and capacity loads. To get these classes of loads the transformer was synchronized with a rotary convertor which was run as a synchronous motor, overexciting it for leading current and underexciting it for lagging current. Knowing the constants, the regulation is found as per sample calculation following.

CALCULATION OF REGULATION.

From test
- Core loss at 110 volts = 47.4 watts.
- Exciting current = 0.918 amperes.

Core loss current $= \frac{47.4}{110} = 0.432$ amp. $= 0.95\%$ of 45.4 amp., full load.

Magnetizing current $= \sqrt{I^2_{ex.} - I^2_{c.1.}} = 0.81$ amp. $= 1.78\%$ of 45.4 amp., full load.

The conventional way of representing a transformer is shown in Fig. 1.

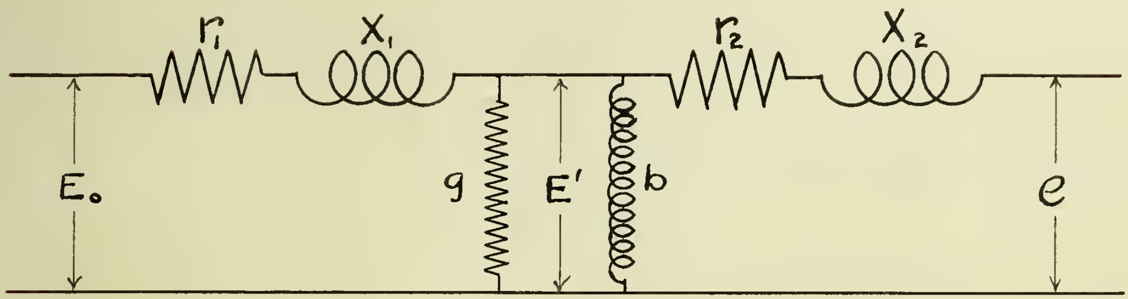


Fig.1.

r_1 = primary resistance. x_1 = primary reactance.

r_2 = secondary resistance. x_2 = secondary reactance.

g = conductance = core loss current in per cent.

b = susceptance = magnetizing current in per cent.

e = e.m.f. at secondary terminals, taken as reference quantity and assumed constant.

E_0 = e.m.f. impressed upon the primary.

In the case under discussion the various quantities have the following values.

$r_1 = 0.00825$. $x_1 = 0.0104$. $I_c = g = 0.0095$

$r_2 = 0.00992$. $x_2 = 0.0104$. $I_m = b = 0.0178$.

$e = 1$.

Secondary current is also taken as equal to 1. On non-inductive load (P.F. = 1), $I_{sec.} = I_{energy} = i$, and i_1, the quadrature

component, is zero. The voltage drop across the secondary is Iz_{sec}. For the general case $I = i + ji_1$, but as stated above, $i_1 = 0$ when P.F. = 1, which is the case under consideration. $z_{sec.} = r_2 - jx_2$. Hence E' the secondary induced voltage is

$$\dot{E}' = e + \dot{I}\dot{z}_s = e + ir_2 - jx_2 = 1 + 0.00992 - 0.0104$$

$$= 1.0099 - 0.0104j.$$

Let I_{oo} = exciting current.

The admittance, $Y_{oo} = g + jb$ and

$$\dot{I}_{oo} = \dot{E}'\dot{Y}_{oo} = (1.0099 - 0.0104j)(0.0095 + 0.0178)$$

$$= 0.0114 + 0.017j.$$

$$\dot{I}_p = \dot{I} + \dot{I}_{oo} = 1 + 0.0114 + 0.17j = 1.0114 + 0.17j.$$

$$\dot{E}_o = \dot{E}' + \dot{I}_p\dot{z}_p = \dot{E}' + (1.0114 + 0.017j)(0.00825 - 0.0104)$$

$$= 1.0185 - 0.0208j.$$

$$E_o = \sqrt{(1.0185)^2 + (0.0208)^2} = 1.0185\%.$$

$$\text{Regulation} = \frac{1.0185 - 1}{1} = 1.85\%.$$

For close and accurate determinations of load division a regulation curve for each transformer should be plotted. For such a curve the regulation should be calculated for 1/4, 1/2, 3/4, 1, 1 1/4, 1 1/2 full load current, and a curve drawn through the points thus obtained.

III. CONNECTIONS.

It is often desirable to determine the effect of certain combinations in the connection of transformers. The correct combination is often difficult to obtain, and certain fundamental considerations must be borne in mind in order to deal intelligently and successfully with the problems.

Obviously, in connecting coils in series the points connected must be of opposite polarity; in parallel connection, they must be of the same polarity, and also the e.m.f.s must be equal and in phase. First let the case of a simple lighting transformer having two primary and two secondary windings be considered. The two primary coils are wound in the same direction around the core. The two secondary coils are wound in the same direction with respect to each other, and may or may not be in the same direction as the primaries. The more common construction is to have them wound opposite to the primary, but this is not always the case and cannot be depended upon without actually testing out.

With both primary and secondary wound in the same direction the polarity of the secondary will be reversed with respect to the primary while with primary and secondary wound in opposite directions, their polarity will be the same.

Let E_o = impressed primary e.m.f.

E_o' = induced primary e.m.f.

e = induced secondary e.m.f.

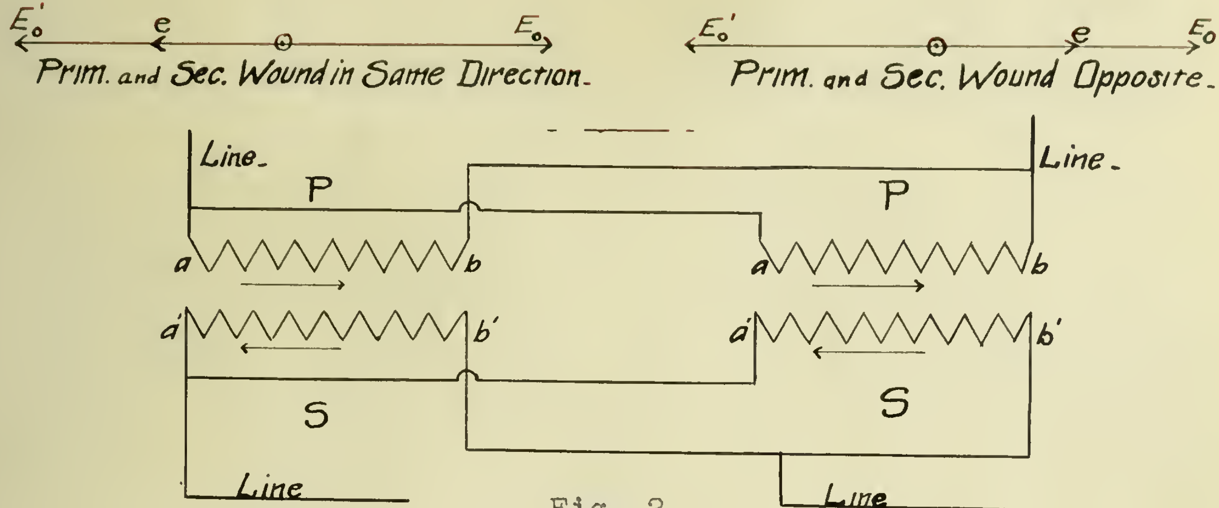


Fig. 2.

The accompanying diagrams show the e.m.f. relations in the two cases. Let Fig. 2 represent two single phase transformers with secondaries wound in the same direction as the primaries. The relative directions of e.m.f.s will be as indicated by the arrows if this is the case, that is, if begining at corresponding points, the two secondary coils follow the same direction of winding around the core. In such a case it is safe to connect the two in parallel by relying on the two sets of binding posts. Thus, we should connect a' points to a' points and b' to b', etc., leading off taps to the line as indicated. However, if one of the secondary coils is wound in the reverse direction to the other secondary the previous connection (see Fig. 2) will cause a short circuit. In this case we should connect as shown in Fig. 3. It is seen that the leads of one transformer are reversed on the secondary side.

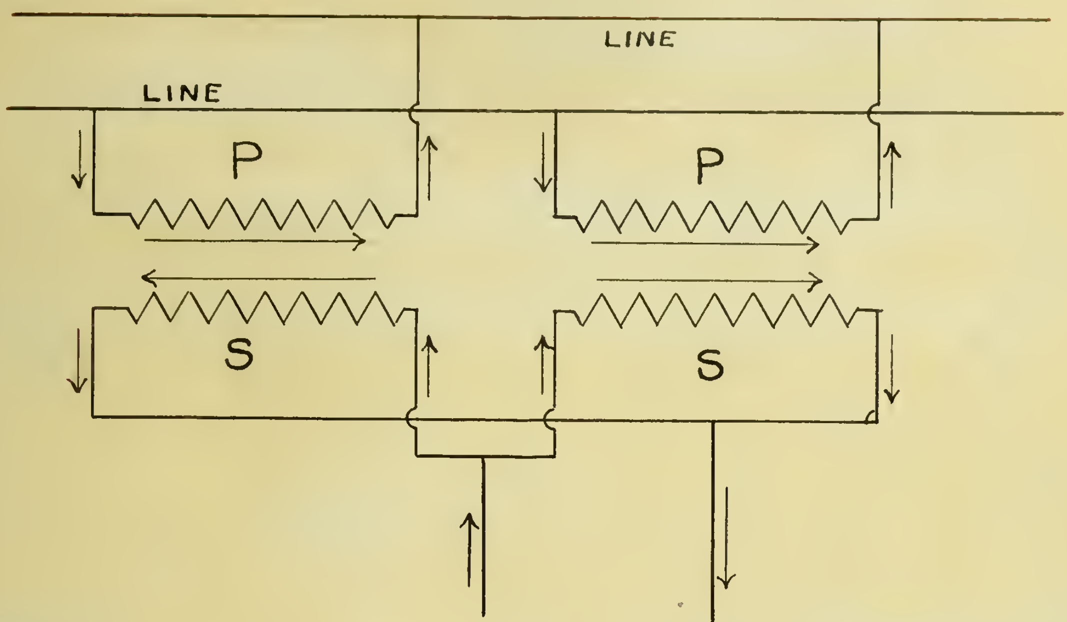


Fig. 3.

In transformers of the same type, a condition such as shown in Fig. 3 would seldom be found. It is not, however, advisable to connect similar leads for parallel operation on transformers of different types, without first determining the way in which the coils are wound.

In three phase systems, three single phase transformers of the same type may be connected by joining the corresponding terminals together, since if of the same type, that is, made by the same company after the same model, they are sure to be similarly wound and constructed. Fig. 4 illustrates the way in which the connections may be made for a $\Delta\ \Delta$.

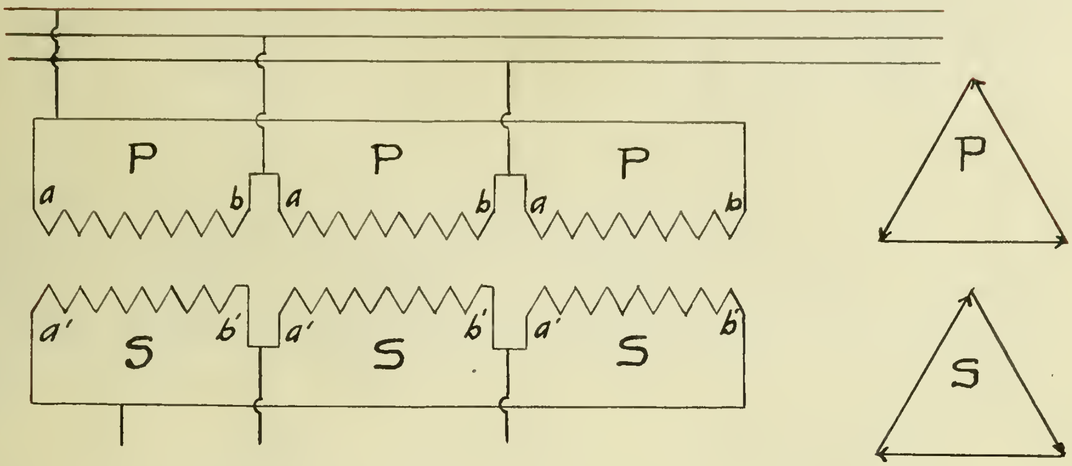


Fig. 4.

The phase rotation is shown by the triangles at the right. This is really what has to be watched for in all connections; the direction of the winding is of importance only because of the fact that it determines the phase rotation, that is, the relative directions of the three e.m.f. vectors at any instant.

A similar set of transformers, connected in the same way, may be banked in parallel with the first set, by connecting corresponding leads, since the phase rotation is identical.

Now suppose that a set of transformers in which the primaries are wound opposite to the secondaries, are put in parallel with another in which the primaries are wound in the same direction as the secondaries. A short circuit is formed if corresponding leads are connected as shown in Fig. 4, since the phase rotation of one set is reversed with respect to that of the other. This phase relation is shown by the diagrams in Fig. 5.

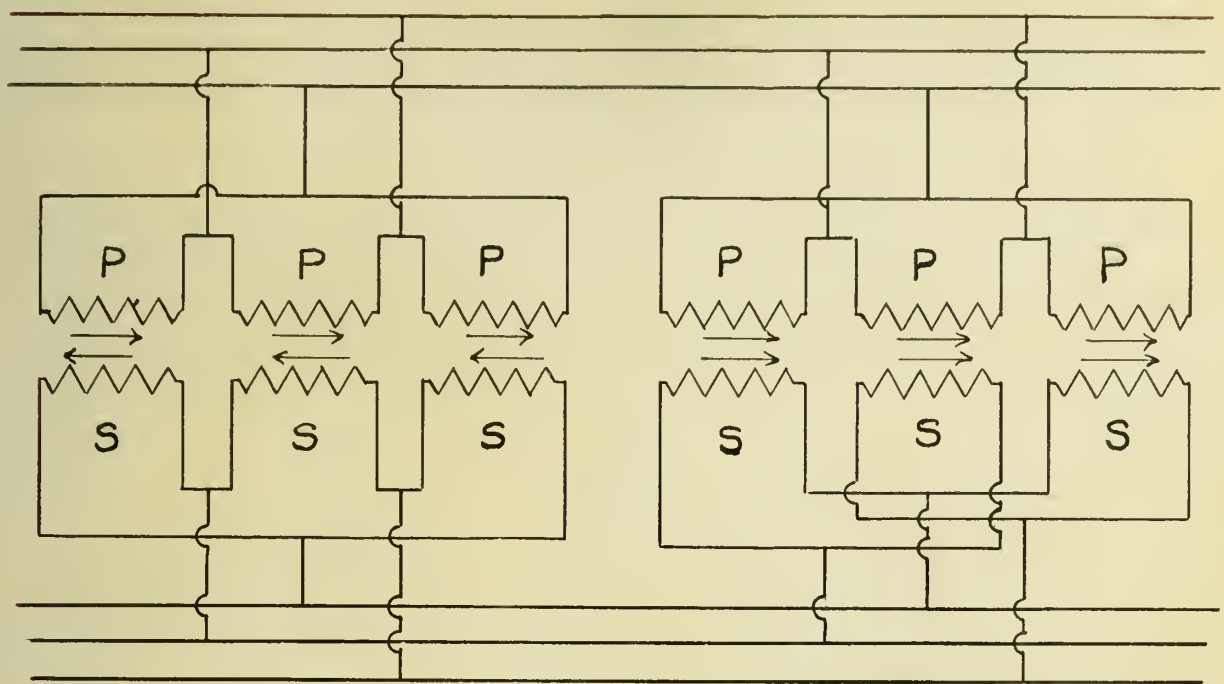


Fig. 5.

Fig. 5 shows the correct method of connecting two sets of transformers in parallel when the coils of the two sets are wound in opposite directions. In such a case the phase rotation in the two banks is opposite and care must be taken to connect the sets so that the phase rotation and e.m.f.s between bus bars shall be correct. Diagramatically the rotation and connections for correct operation are as shown in Fig. 6.

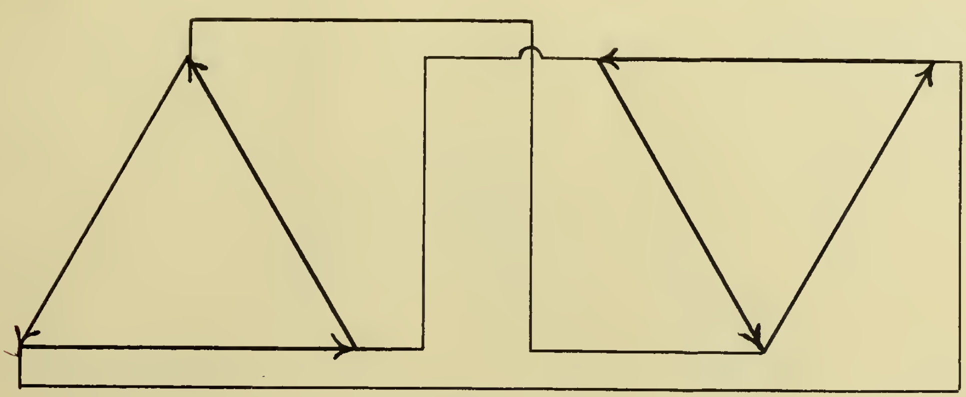
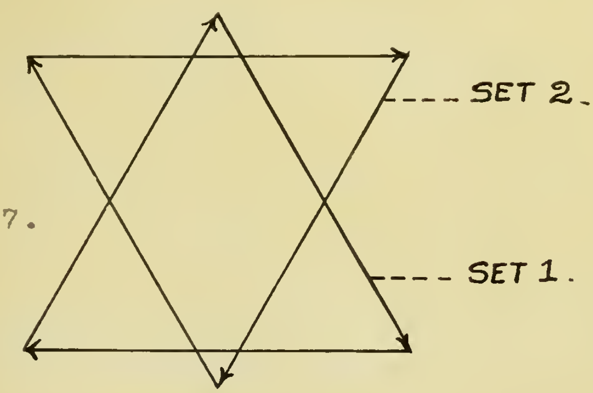


Fig. 6.

It will be noticed that vectors of like direction are joined together, and also points of equal potential, that is, arrowhead to arrowhead etc. With two sets of transformers with secondaries wound in opposite directions a six phase relation is really obtained. This becomes apparent if the vector diagram of one set is superimposed upon that of the other. See Fig. 7.

Fig. 7.



This is the general case, and holds for all combinations such as $\Delta_p\Delta_s$ with Y_pY_s, Δ_pY_s with $Y_p\Delta_s$ etc., except for the case of a $\Delta\Delta$ paralleled with a ΔY or $Y\Delta$. Considerable time was spent trying to get a combination of this kind to work successfully. For a time it was thought that something was wrong in the connections, but reversing them did not change the voltage ratios obtained across certain points of the secondaries. It was then concluded that something was wrong in the fundimental theory, and investigation by means of vector diagrams showed that it was impossible to parallel the $\Delta_p\Delta_s$ set with the $Y_p\Delta_s$ set.

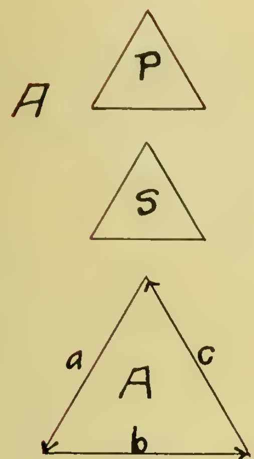
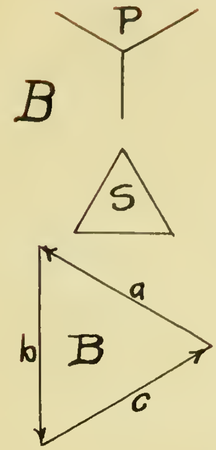


Fig. 8.



The vector relations are shown in Fig. 8. It is seen that the vectors of set B are perpendicular to those of set A. Reversing a lead neither puts the vectors in phase nor at 180° to each other, as it does with other combinations. Since no two of them are ever parallel to each other it is not possible to connect so that a voltage may be obtained which is either equal to or double that of a single coil. The vectors being perpendicular, it is easily seen why no change in voltage ratio was obtained by reversing connections.

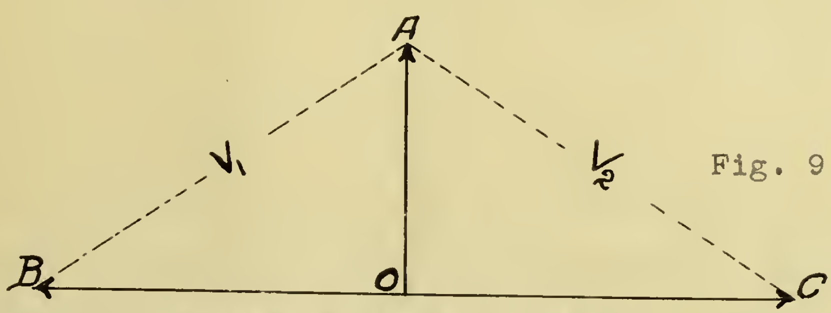


Fig. 9.

Suppose the drop between the two points A and B measured. Then if OB is reversed, B falls at C, and it is apparent that the voltage V_2 between A and C will be of the same magnitude as V_1 between A and B.

If OB = OA, $\angle$ OBA = $\angle$ OAB = 45°. Hence AB = $\sqrt{2\ (OB)^2}$, or $\sqrt{2\ (OA)^2}$.

Data taken in an actual test shows the effect of the vector relation in $\Delta\Delta$ with $Y\Delta$ discussed above. Two sets of transformers were connected to the line with their primaries Δ and Y respectively. The secondaries were then connected, each in Δ and tests begun to see if the two systems could be paralleled. Before any connection was made between the sets, the phase relation in the secondaries was as shown in Fig. 10 below, where a b c represent the e.m.f. vectors of one set and a' b' c' those of the other. Points a and a' were connected together; the effect upon the diagram is shown by Fig. 11.

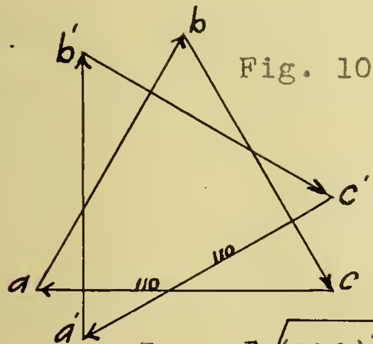


Fig. 10.

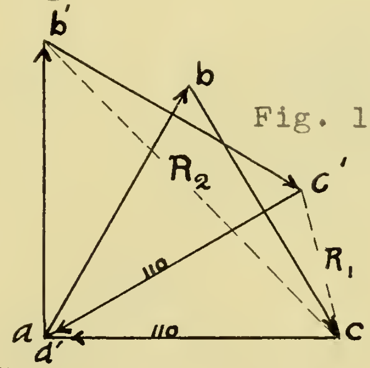


Fig. 11.

$$R_1 = \sqrt{(110)^2 + (110)^2 - 2 \times 110 \times 110 \cos 30}$$

$$= 58 \text{ volts.}$$

$$R_2 = \sqrt{(110)^2 + (110)^2} = 156 \text{ volts.}$$

Now if the phase relation was correct for paralleling, the two diagrams would coincide, that is, points b and b' would be at the same potential and also points c and c'. Actually, the voltage between points c and c' was 58 volts, that between c and b' 156 volts.

One coil, represented by vector a'c', was then reversed to see if this would give the desired voltage. The diagrams

representing the e.m.f. relations after this change are shown in Fig. 12.

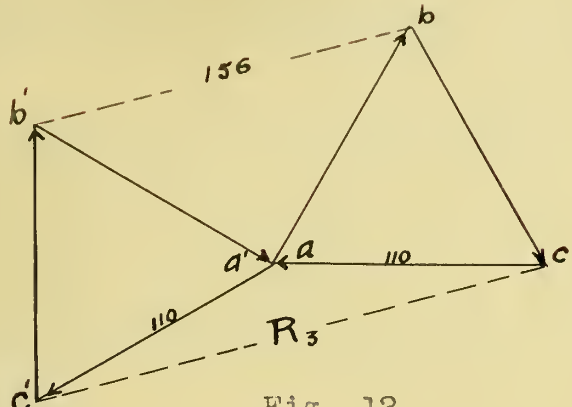


Fig. 12.

$$R_3 = \sqrt{(110)^2 + (110)^2 + 2 \times 110 \times 110 \cos 30}$$
$$= 213 \text{ volts.}$$

The voltage between c and c' was now found to be 213 volts, the same between c and b', and that between b and b' to be 156 volts.

IV. EFFECT OF CHANGING FREQUENCY UPON THE OPERATION OF A TRANSFORMER.

The fundamental equation for the e.m.f. induced in a transformer is

$$E_{eff.} = 2\, fn\phi \times 10^{-8} \text{ volts} \quad \ldots\ldots\ldots\ldots (1)$$

where $E_{eff.}$ = effective value of the e.m.f.

f = frequency.

n = number of turns cut by

ϕ, the flux.

From (1) is obtained

$$\phi = \frac{E \times 10^{8}}{kf} \quad \ldots\ldots\ldots\ldots, (2)$$

It is apparent that with a constant e.m.f. at the terminals the flux will vary inversely as the frequency. The hysteresis loss depends upon the flux per unit area as shown by the hysteresis formula:

$$W_h = nVfB^{1.6} \times 10^{-7}. \quad \ldots\ldots\ldots\ldots (3)$$

where n is a constant depending upon the construction constants and units used.

V is the volume of the iron (cu.in. or cu. cm.)

B is the flux in lines per square inch or centimeter.

f is the frequency.

W_h is the loss in watts.

Apparently then, the hysteresis loss will increase rapidly with increasing flux density, that is with decreasing frequency,

since $B^{1.6}$ offsets the effect of the decreased value of f. Practically, however, it was found that this increase was not excessive. The total watts loss on open circuit was in most cases about double for 30 cycles what it was for 60 cycles, but the I^2R of the high magnetizing current at 30 cycles figured largely in the readings taken at that frequency.

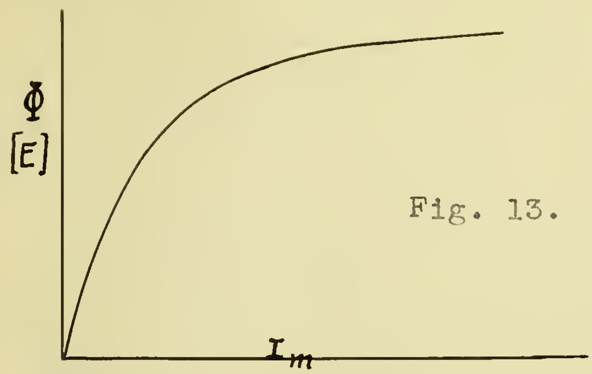


Fig. 13.

The magnetization curve for ordinary transformer iron has somewhat the shape shown in Fig. 13. For the minimum cost and weight per K.W., transformers are designed to operate near the knee of the curve. Inspection of the curve shows that above the knee a slight increase in voltage, or flux, necessitates a large increase in magnetizing current. Now the old transformer iron possessed the property of high permeability, that is a given value of magnetizing current would send more flux through this iron than the same value will send through the iron of which the transformers of the last three or four years are built. Hence to increase the flux through this iron required a much smaller increase in I_m than that increase requires in the more recent iron. On the other hand, the modern iron can

be worked at a much higher density, that is nearer the knee of the saturation curve, than the older iron, with the same core loss. This is what is actually done in modern transformer design.

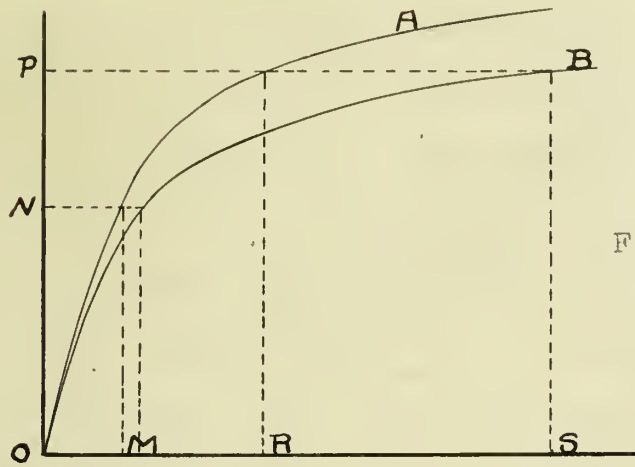


Fig. 14.

Fig.14 shows the effect of increasing the flux as is necessary when operating at a frequency below normal. Suppose that ON represents the flux necessary to give normal voltage at rated frequency, and let OP represent the flux necessary to give the same voltage at a lower frequency. At normal frequency the two transformers take about equal magnetizing currents OM, say. Then since B is worked so much nearer the knee of its saturation curve it will require magnetizing current equal to OS, while A requires only OR.

It was very interesting to watch the working out of this theory. It was impossible to get normal voltage at 30 cycles on some of the transformers, due to the fact that the generator used, which was the only one available for 30 cycles, became heavily overloaded by the magnetizing current drawn. It was possible to get readings over a fairly wide range in all cases,

however. The 5 K.V.A. G.E. transformer is a recent product of the company and is made of the modern silicon iron. Reference to the curves shows that it operated worse on 30 cycles than any of the other transformers tested, and yet it operated with much lower magnetizing current on 60 cycles than any of them, beside having a better regulation. Thus curves on page 22 show that on 60 cycles full normal voltage requires about 0.8 ampere, while on 30 cycles 0.8 ampere gives a voltage that is scarcely appreciable and normal voltage could not be obtained within the limits of the apparatus used. More than full load current flowed in the transformer windings and the generator was overloaded about 150%. In round numbers it would have taken in the region of 55 amperes to give 110 volts. This is about 70 times the magnetizing current drawn on 60 cycles.

On the other hand, the old Ft. Wayne transformer tested shows that it could be operated on 30 cycles with a little over eight times normal magnetizing current at 60 cycles. See curves on page 23.

G.E. transformer #313658 was an old type also, but seemed to possess about the same iron characteristics as the 5 K.W. referred to above. It is inferior to the 5 K.W. in regulation and in most of its constants, and it was expected that it would behave fairly well on 30 cycles. It is seen from the curves that it failed to perform within any reasonable limits at this frequency, however. Since this was probably not the modern iron, this behavior was doubtless due to some peculiarity in design,

which caused the iron to be worked at a density high on its' saturation curve at normal frequency.

The Westinghouse transformer operated well at 60 cycles, and is modern in design. The curves on page 24 show its' behavior on 30 cycles and 60 cycles.

The following table gives the constants of the different transformers, thereby indicating the care and quality in design and construction, the last two columns showing the effect of halving the frequency.

TABLE I.

Transformer.	Total R	Total X	Total Z	Reg.	I_c 60	I_c 30	I_m 60	I_m 30
G.E. #745828 5 K.V.A.	1.82	2.08	2.77	1.85	0.95	3.10	1.78	120
Westinghouse 3 K.V.A.	1.92	2.31	3.00	1.96	1.12	2.20	1.87	80
Ft. Wayne #48854 2 K.V.A.	2.165	1.77	2.80	2.31	2.75	5.20	2.85	35
G.E. #313658 2 K.V.A.	1.24	2.69	2.96	2.52		5.90	8.75	144

It was impossible to get the magnetizing current at 110 volts for the Westinghouse and G.E. transformer # 313658 at 30 cycles. In these cases I_m was figured at the highest available voltage, this being 95 volts in each case.

This excessive magnetizing current does not always prohibit operation on 30 cycles for 60 cycle transformers, although it

is always the source of excessive I^2R losses compared to 60 cycle I^2R losses.

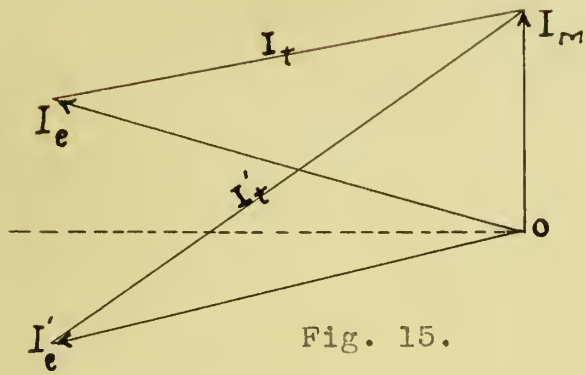


Fig. 15.

Let I_e = energy current, leading.

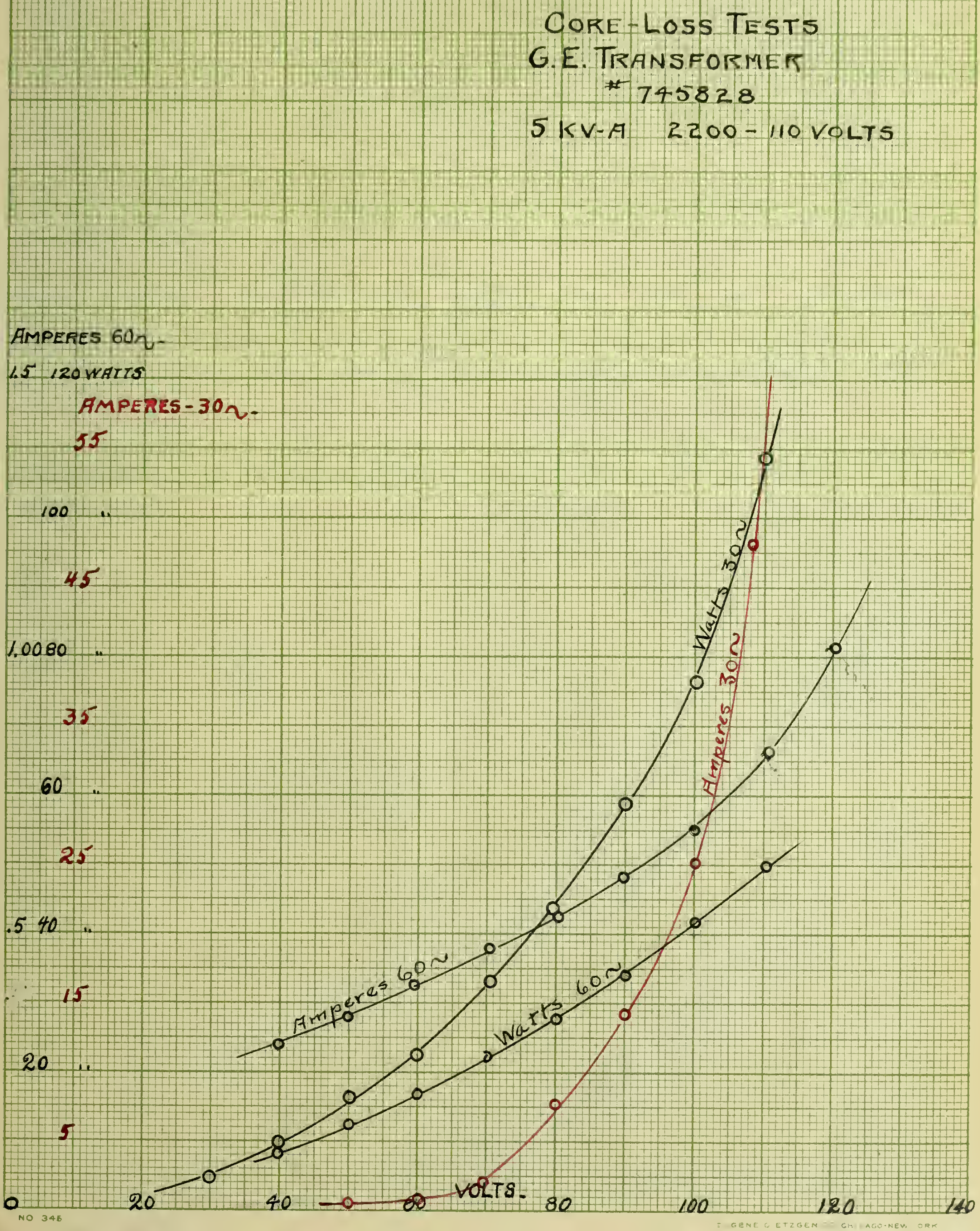
I'_e = energy current lagging.

I_m = magnetizing current.

Then I_t and I'_t show the total current in the two cases. It is obvious that I_t is much smaller on capacity load than on inductive.

A high value of I_m gives a very poor power factor for the transformer and this is objectionable. As a rule, a high magnetizing current will give a poor regulation, although the other constants may be such that the transformer will have a good regulation in spite of I_m. For example, transformer #313658 has 8.75% magnetizing current, but the regulation figures out to be 2.52%, a figure well within the specifications of a good machine.

The power factor on most transformers in use to-day is above 0.99 with full non-inductive load.


CORE-LOSS TESTS
G. E. TRANSFORMER
745828
5 KV-A 2200 - 110 VOLTS
AMPERES 60~.
1.5 120 WATTS
AMPERES - 30~.
55
100 "
45
1.00 80 "
35
60 "
25
.5 40 "
15
20 "
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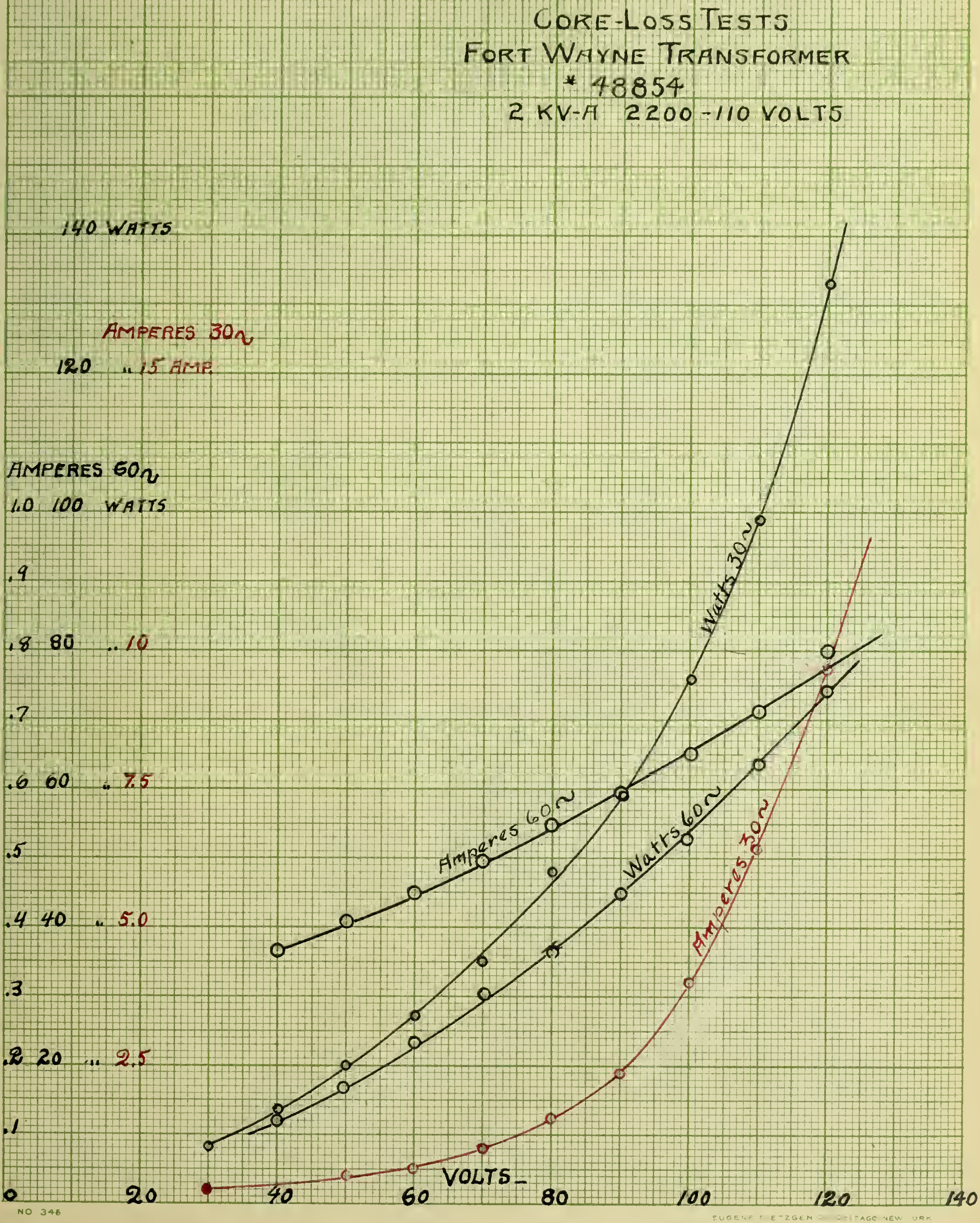

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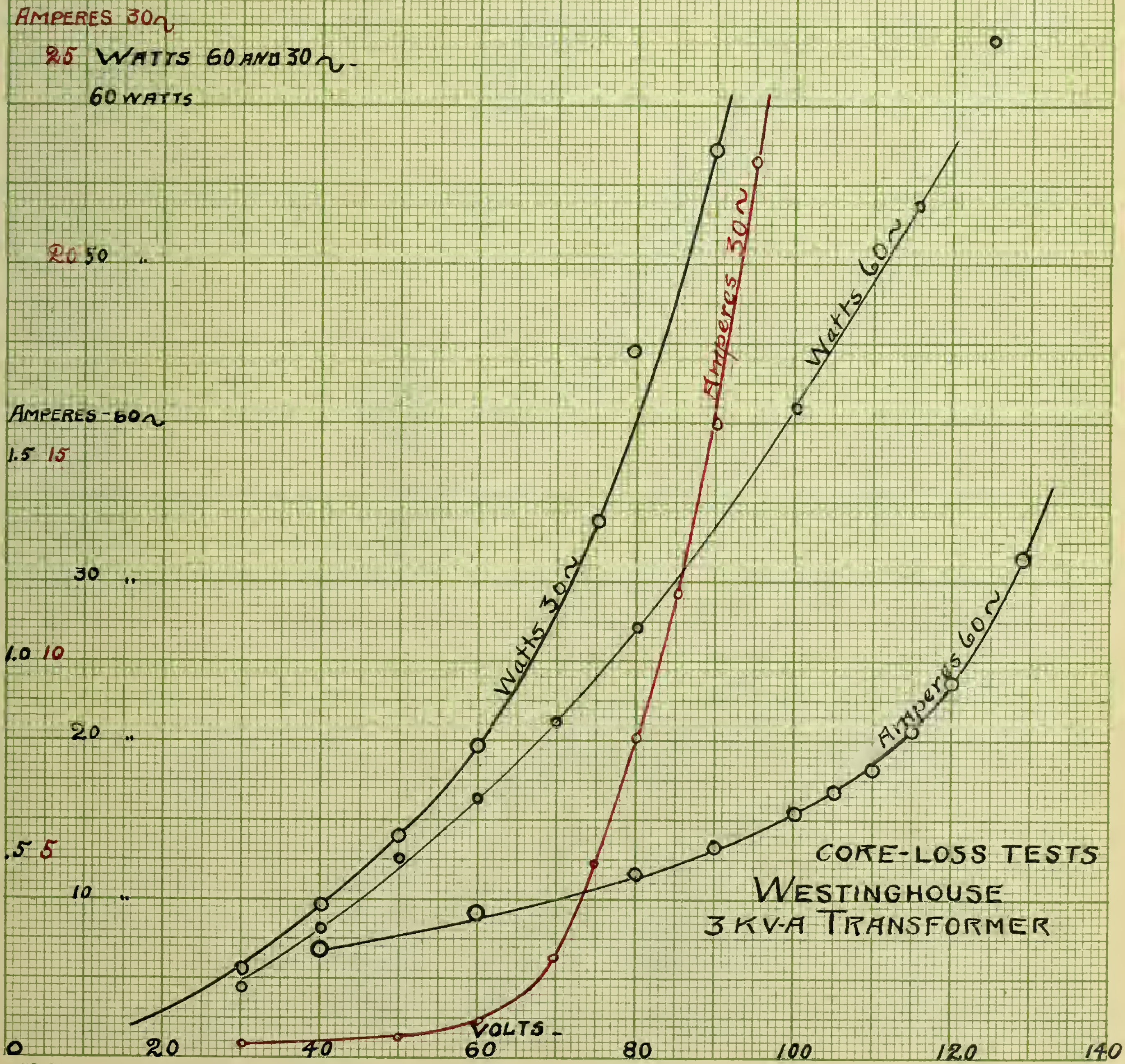

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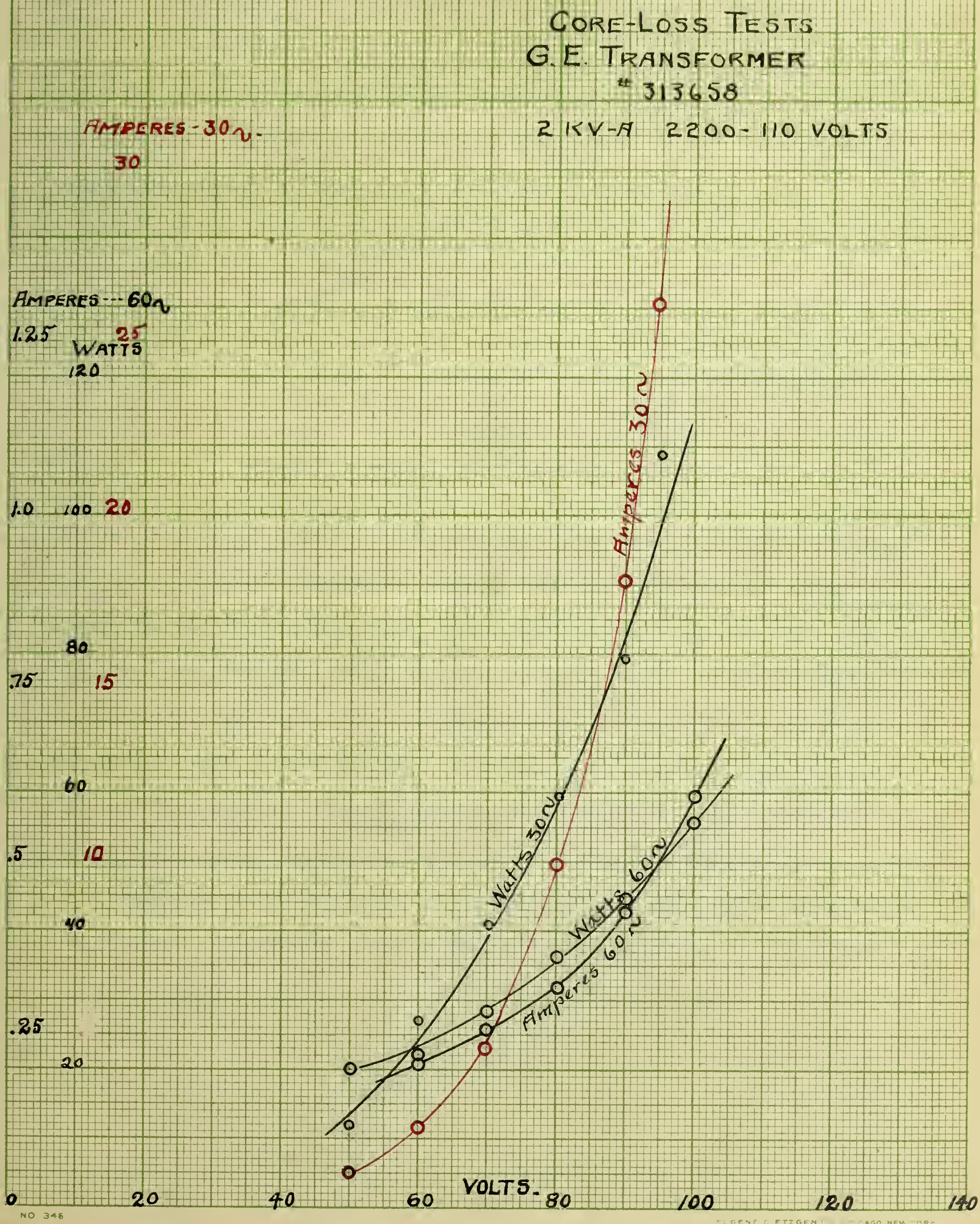
CORE-LOSS TESTS
G. E. TRANSFORMER
313658
2 KV-A 2200-110 VOLTS
AMPERES-30~
AMPERES---60~
WATTS
30
1.25
25
120
1.0
100
20
80
.75
15
60
.5
10
40
.25
20
Amperes 30~
Watts 30~
Watts 60~
Amperes 60~
VOLTS.
0
20
40
60
80
100
120
140
NO 346

V. OPEN DELTAS.

It often occurs in three phase work that one side of a delta, that is, one transformer, fails and is not operative in supplying power to the load, as shown in Fig. 16.

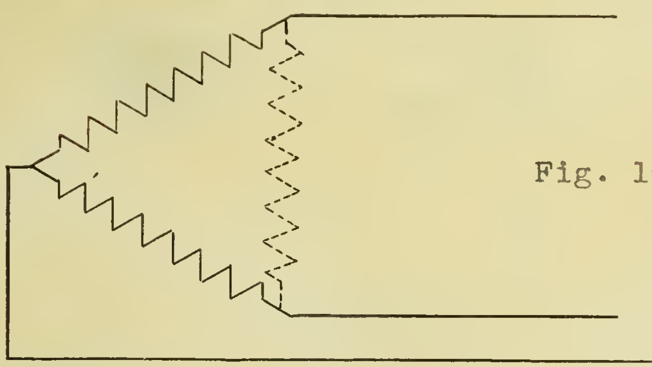

Fig. 16.

The system will still operate as a three phase system, but will overload the two remaining transformers. Suppose the power taken to be constant. Then what was before line current now becomes the current flowing in each coil and is greater than the former coil current, the ratio being $\sqrt{3} : 1$. This obviously overloads the transformers. For the same heating and losses in the coils as occur when the delta is complete $\frac{1}{\sqrt{3}} = 0.578$ of the closed delta power may be taken from the lines.

Two transformers connected open delta were paralleled with two others similarly connected, and load put upon the system. Fig. 17 shows the connections and the instruments.

Table II shows the current in different parts and the voltage across the secondaries of each of the four transformers.

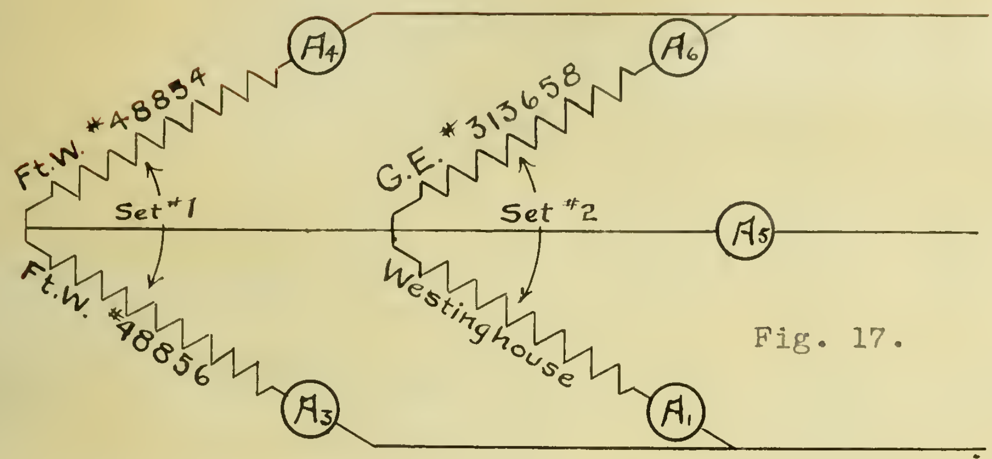

Fig. 17.

TABLE II.

A_1	A_3	A_4	A_5	A_6	Vcoil Westing. & 48856.	$V_{G.E.}$	V_4[illegible]54	$V_{open.}$
23.10	1.6	19.6	36.0	18.7	110	107.0	107.0	107.0
19.60	13.4	16.7	30.0	15.7	110	107.0	107.0	107.0
15.65	10.7	13.6	24.0	12.5	110	108.0	108.0	107.5
11.80	8.0	10.3	18.6	9.3	110	108.0	108.0	108.6
8.10	5.3	7.3	12.4	5.6	110	109.0	109.0	109.0
6.10	4.0	5.3	9.2	4.0	110	109.0	109.0	109.0

It appears from this data that the transformers would operate very well when connected in this manner. This data was taken for non-inductive load. Table III shows the load division on inductive and capacity loads. These were obtained by synchronizing the transformers with a synchronous motor and varying the excitation of the latter.

TABLE III.

No	A_1	A_3	A_4	A_5	A_6	Westing. Ft.Wayne	48854 313658	Open Voltage set #1	Open Voltage set #2	W_1	W_2
1	21.0	13	16.0	34.0	15.5	110.5	112	110.0	110	-140	3000
2	18.5	7.8	14.8	25.7	14.5	110.5	112	108.7	109	2600	-200

No. 1 is inductive load. P.F. = 0.44

No. 2 is capacity load. P.F. = 0.47

On these classes of loads it is apparent that unequal division is likely to occur, the transformer with the better regulation tending to take an undue share of the load. Thus the Westinghouse, which has closer regulation than the Ft. Wayne paralleled with it, takes from 62 to 137 percent more current than the latter transformer altho it is only 50 percent larger.

If four transformers were available for three phase work it would be better to take three of them for a closed delta than to operate the four in parallel open delta. In the first case, to give the same power to the line each transformer would be overloaded 15.5 percent of open delta load, considering equal load division among them. This load division should remain stable for all classes of loads however, and most transformers will not suffer from 15.5 percent overload. With the paralleled open deltas it was just seen that unbalancing is very likely to occur and this might go so far that the transformer which tended to take the load would be burned out.

VI. CONCLUSIONS.

Definite conclusions in a paper of this kind are difficult to draw, since the nature of the work done has not been such as to warrant any very definite conclusions. The value of the work lies more in the working knowledge gained than in new disclosures. To sum up briefly, the following points may be emphasized.

(1) The constants of a transformer should be considered when parallel operation is desired since they affect the regulation and thereby the load division.

(2) Sets of transformers may not be connected in parallel unless the phase rotation in each set is identical and unless points of equal potential are joined together. On account of the phase relations a $\Delta\Delta$ cannot be paralleled with a $Y\Delta$.

(3) Transformers may be operated satisfactorily at a frequency higher than rated, the only objection being that the reactance is increased and thereby the regulation made poorer. At a lower frequency, however, the magnetizing current is excessive and the operation very poor for values much below normal.

(4) Open deltas in parallel appear to be satisfactory for non-inductive loads, but for other classes of load are likely to give trouble from unequal load division.

A closed delta, even with the individual transformers overloaded 30 or 40 percent, will give better service as a general rule.

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